Europa Clipper Thermal Control Design

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This paper details the design developments of the Europa Clipper spacecraft thermal control system and its primary element the Heat Redistribution System (HRS). The Europa Clipper spacecraft will launch in the early 2020s and will have multiple flybys of Jupiter's icy moon, Europa. The HRS, which utilizes a Mechanically Pumped Fluid Loop (MPFL) to reclaim waste heat from an avionics vault module and redistribute it to the propulsion module and radiator, has become an integral part of the spacecraft architecture both in terms of mechanical configuration and spacecraft operations capability. A walkthrough on the planned implementation of the HRS on the primary spacecraft modules is provided along with a description on thermal control of spacecraft hardware not located on the HRS vault, where thermal isolation and tolerance to extreme thermal environment drives the hardware designs.

Nomenclature

AFT	=	Allowable Flight Temperature
APL	=	Applied Physics Laboratory
AU	=	Astronomical Unit
CFC-11	=	Tricholorofluoromethane (Freon)
EIS	=	Europa Imaging System
HGA	=	High Gain Antenna
HRS	=	Heat Redistribution System
ICEMAG	=	Interior Charectorization of Europa using Magetometry
IPA	=	Integrated Pump Assembly
MEV	=	Maximum Expected Value
MLI	=	Multi-layer Insulation
MV	=	Mixing Valve
NAC	=	Narrow Angle Camera
PCA	=	Pressurant Control Assembly
PIA	=	Propellant Isolation Assembly
REASON	=	Radar for Europa Assessment and Sounding: Ocean to Near-surface
REM	=	Rocket Engine Module
RHB	=	Replacement Heater Block
RF	=	Radio Frequency
SA	=	Solar Array
SADA	=	Solar Array Drive Assembly
SIRU	=	Scalable Inertial Reference Unit
SRU	=	Stellar Reference Unit
TV	=	Throttle Valve
TWTA	=	Traveling Wave Tube and Amplifier
UVS	=	Ultraviolet Spectrograph
WAC	=	Wide Angle Camera
WU	=	Wheel Unit

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I. Introduction

Europa Clipper is a planned JPL/APL managed NASA mission with a launch date of 2022. The objective of the mission is to investigate Europa, Jupiter's 4th largest moon, and provide further insight into the surface composition, ice shell thickness, and surrounding magnetosphere and ionosphere of the moon. The spacecraft will orbit Jupiter and observe Europa primarily during a series of four-day observation windows enveloping each orbit's closest approach of the moon. This trajectory helps in reducing the total ionization dose the spacecraft must design to as the majority of the orbit is outside of the worst portion of the Jupiter's radiation environment Figure 1.

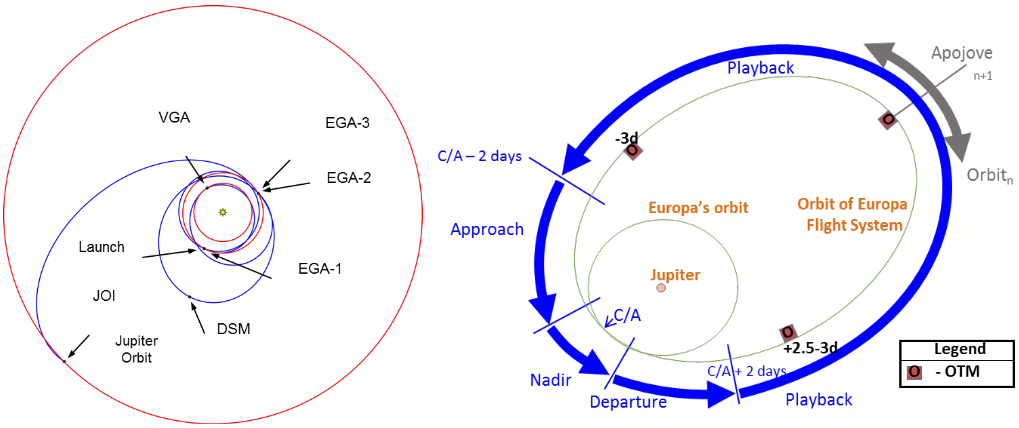

Figure 1. Mission Trajectory for Europa Clipper a) Interplanetary Trajectory (Left) b) Jupiter Orbit (Right).

Depending on the launch vehicle used, the cruise to Jupiter can take 2 years (direct cruise) or 7 years (indirect trajectory). The indirect trajectory, as shown in Figure 1, will take the spacecraft inner cruise for a Venus gravity assist, with a closest distance from the Sun being 0.65 AU. At Jupiter the spacecraft will be as far as 5.6 AU from the Sun. This translates to a two order of magnitude range in solar heating that the spacecraft will have to accommodate. During the science tour, the spacecraft will experience Europa and Jupiter Eclipses, with the spacecraft having to accommodate eclipse durations as long as 9.2 hours.

II. Flight System Overview

The flight system, defined as the spacecraft and instrument components, uses solar arrays as its source of power generation and a 330 –A-hr battery used during eclipses and high peak power states. Because of the large Sun distances and harsh Jupiter radiation environment, solar array power generation at the end of mission (EOM) is 650W.

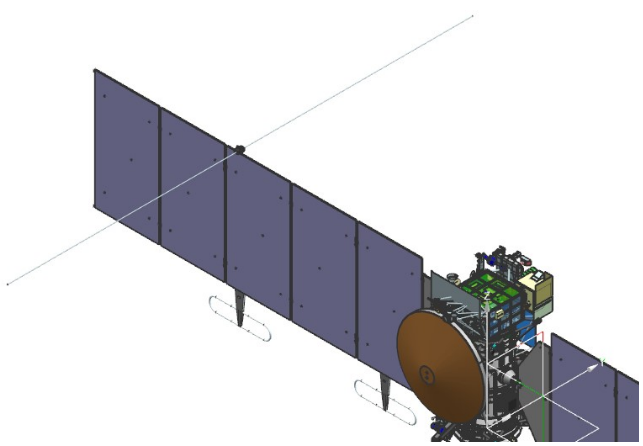

Figure 3: Isometric view of the Europa Clipper Flight System.

The spacecraft is composed of three primary assemblies: the avionics module, the propulsion module, and the RF module. The avionics module houses the majority of spacecraft and instrument electronics boxes inside an aluminum vault that serves as protection from the harsh radiation environment at Jupiter. Seven instrument sensor heads are also located in the avionics module, with the majority located on an optics bench platform called the nadir deck. Star trackers and instruments requiring Europa pointing during the flyby are mounted onto this deck; two visible spectrum sensor heads (EIS NAC and WAC), a thermal imager (E-Themis), and a UV spectrograph (Europa UVS). The avionics module also houses three other instrument heads: three directly mounted on the external panels of the vault (MASPEX, MISE, SUDA), and one (PIMS) on a bracket on top of the High Gain Antenna (HGA).

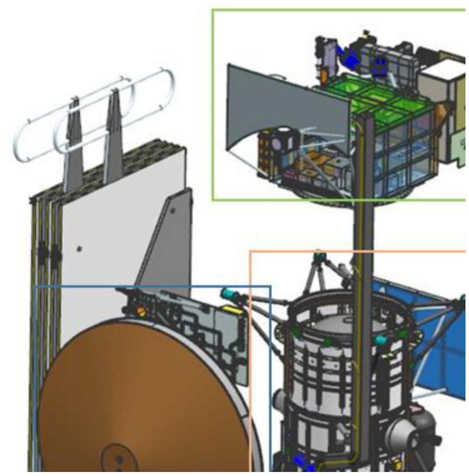

Figure 4: Breakdown of the spacecraft by modules.

The RF module is composed of telecom hardware including the 3m diameter HGA, a Mid Gain Antenna, a set of Low Gain Antennas, Fan beam antennas, and an RF panel with radios and TWTAs. Waveguides run from the different antennas, through the propulsion module, and to the RF panel. All of these components are mounted onto the largest module of the spacecraft, the propulsion module.

The propulsion module houses the bi-prop system propulsion hardware; the prop tanks are inside the cylinder structure while the pressurant tanks are mounted external to the cylinder. Four rocket engine modules (REMs) house 24 individual engines and propellant lines run throughout the entire system. The spacecraft radiator and replacement heater block (RHB) are also mounted on the external part of the propulsion module. The Solar Array Drive Assemblies (SADA) and magnetometer boom are also mounted on the propulsion module. The solar array carries several antennas for the REASON science investigation, and the magnetometer boom carries a set of magnetometer sensors making up the ICEMAG science investigation.

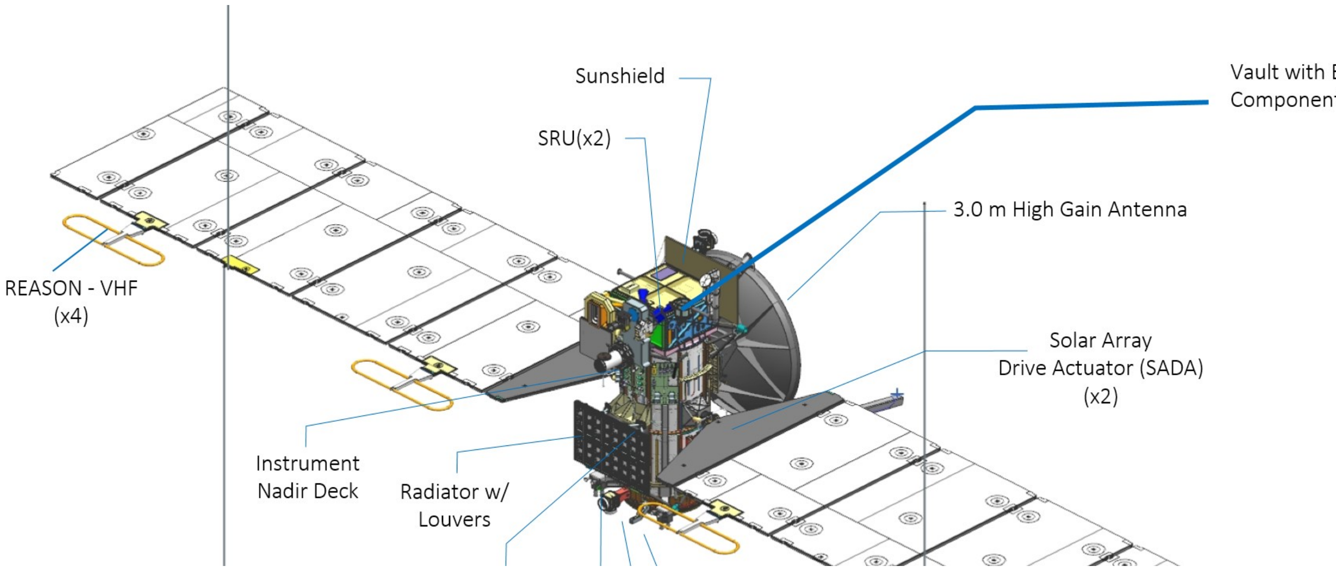

Figure 5: Hardware highlights of the Europa Flight system.

III. Thermal Subsystem Overview

The requirements of the thermal subsystem are to maintain the spacecraft hardware within the allowable flight temperatures for all flight conditions all the while fitting within the allocated mass and power. The allowable flight temperatures - simplified to the assembly level - are provided in Table 1. The vault electronics have wider limits than the propulsion subsystem hardware and these two types of components are what drive the module-level temperature requirements. The battery, mounted on one of the external faces of the vault, does have narrower limits than the rest of the vault mounted hardware,(0℃ to 30℃) . RF antennas, the solar arrays, and the magnetometer boom tolerate much wider temperatures. Instrument sensor heads have a variety of temperature ranges at which they operate and their individual, separate thermal control is responsible for achieving those temperatures.

Table 1: General temperature requirements for Europa Clipper assemblies.

	Allowable Flight Temperatures, ℃	
	Operating/Non-operating	
Assembly	**Min**	**Max**
Vault	-20	50
Nadir deck	-60	30
Propulsion Module	0	35
Radiator	-95	40
RF Antennas	-135	105
HGA/Boom	-200	100
Solar Arrays	-238	100

Europa Clipper is a power-starved system, hence the efficient and effective use of electric and thermal power by the thermal control system is critical. The approach taken to meet these subsystem requirements and constraints are to: (1) efficiently use a mechanically pumped fluid loop to manage waste heat generated from the vault and redistribute it to other parts of the spacecraft (i.e. the propulsion hardware); (2) thermally isolate hardware that can tolerate much wider temperatures. Through these approaches, the subsystem is able to reduce total heater power demand and flight system peak power demand.

A. Heat Redistribution Ssystem (HRS) Thermal Control

Figure 6 shows a simplified diagram of the HRS thermal control. Heat dissipation from the electronics boxes inside the vault is harvested and transported to the propulsion module with the use of the HRS. There is a minimum amount of heat required for the propulsion hardware to stay above the minimum temperature requirements. Whenever the vault dissipation is not sufficient, a Replacement Heater Block (RHB), is used to supplement additional heat. Conversely, heat is rejected out to space through the spacecraft radiator whenever there is excess heat dissipation in the vault assembly and propulsion module assemblies. To dial down the amount of heat loss through the radiator during cold cases, a set of passive oil-actuated valves modulate the amount of fluid flow to the radiator versus a radiator bypass leg. Heaters are required to maintain the trickle flow of the fluid above its freezing limit because the valves can significantly reduce fluid flow through the radiator. The final thermal switch employed are louvers on the radiator, which help in maintaining the radiator heater power demand low. The vault assembly, RF Panel, and primary propulsion module structures (cylinders and rocket engine modules) make up the spacecraft portion of the HRS. Additionally, the RHB, mixing valve/throttle valve, and Louver manage the heat in the HRS. Detail on HRS centric design and trade studies can be found in Reference 1.

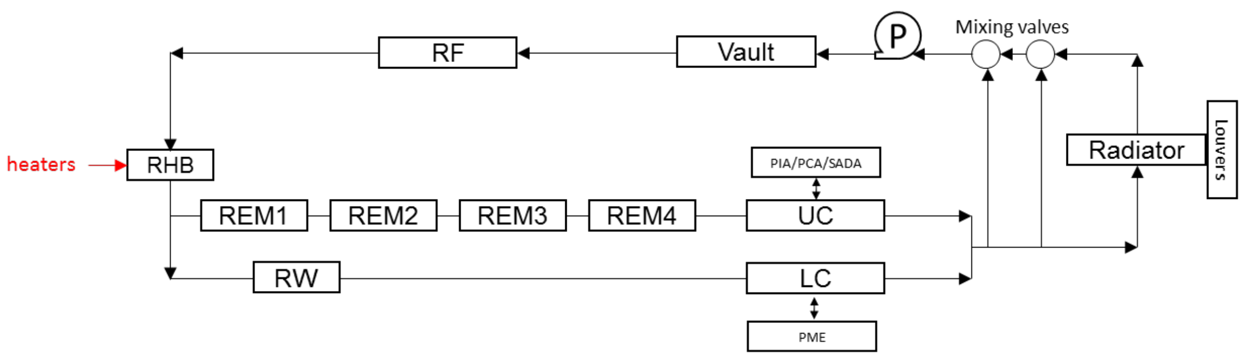

Figure 6: High level description of the Europa Clipper HRS. Note: UC = Upper Prop Cylinder, LC = Lower, RW = Reaction Wheel Prop Cylinder.

The HRS is critical in helping to reduce the amount of electrical power required for heaters and peak power demand of the flight system. This is due in part to the nature of flight system operations at Jupiter. Most of the science observation occurs primarily at and around closest approach of Europa. Power demand is at its highest during these flyby windows and stored battery energy supplements the power generated by the solar array. Since the HRS is able to harvest the excess waste heat generated by the vault electronics and use it to heat the propulsion module, the amount of electrical heater power required during these flybys is lower than a fully passive thermal control architecture. Architecture trade studies relating to this can be found in Reference 2.

B. Avionics Module HRS Control

Beginning at the pump and the Integrated Pump Assembly (IPA), the first set of components on the fluid loop are the vault-internal hardware shown in Figure 7. Three of the six vault panels have HRS routing. The battery panel, (-Y panel), is first on the loop due to the tight battery temperature requirements and preference of relatively cool temperatures during inner cruise: the hottest environment of the mission. The Wheel Drive Electronics (WDEs) are also located on the battery panel. The fluid loop then passes to the base panel, (-Z Panel), of the vault where the majority of the vault electronics are mounted. The fluid loop passes aligned to the bolt pattern of the electronics boxes to the best extent possible. The 5 mm thick panel required for radiation shielding allow for a simple routing design compared to the design of other JPL HRS systems. Finally, the fluid loop passes by the +Y panel where the Scalable Inertial Reference Units (SIRUs) are mounted to. The remaining two side vault panels (+/-X panels) do not contain hardware, hence the fluid loop is not routed to these panels. The top panel, (+Z panel), is a close out panel with only a few electronics boxes, most of which only operate for short durations during the science flybys. Due to the 10 mm thick vault panels, the side panels and fluid loop are sufficient to be able to maintain the +Z panel within the required temperature limits. There is a small penalty in the harvesting efficiency of heat dissipated at this panel, however the complexity in design and implementation in adding HRS passes on this panel outweighs the small harvesting impact.

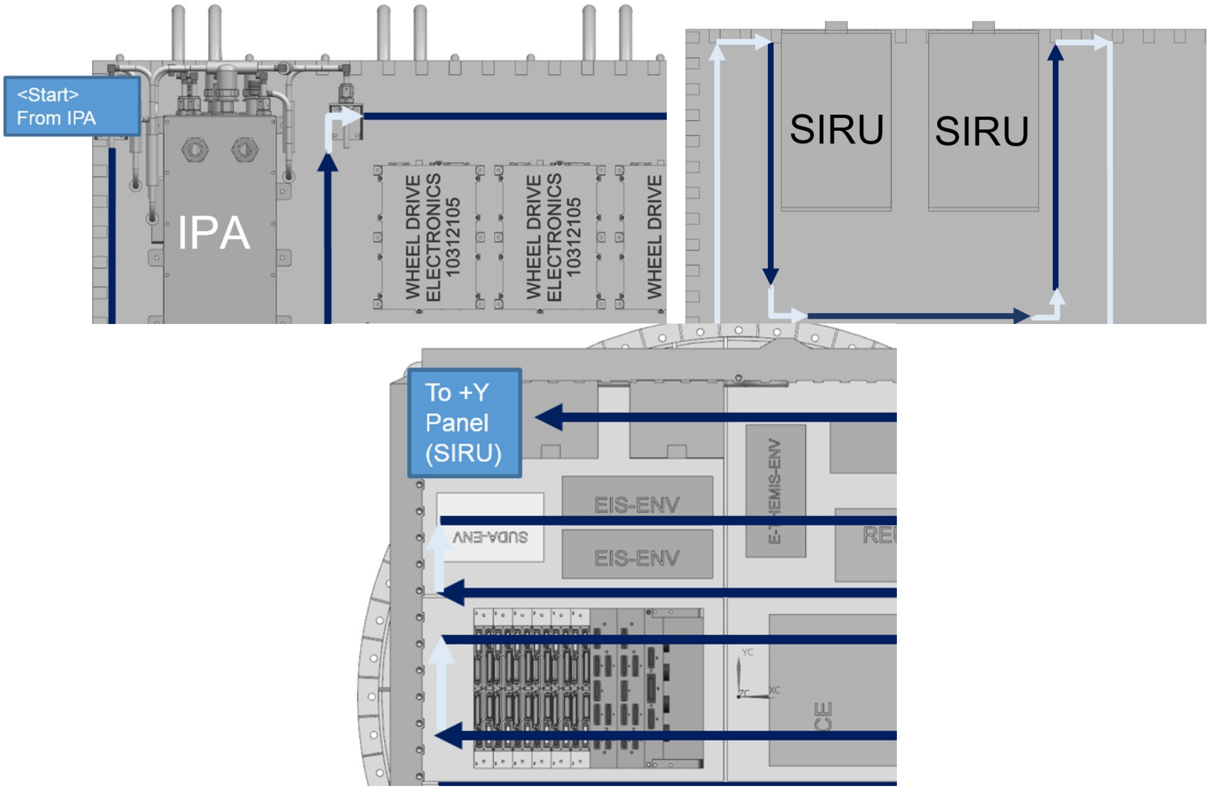

Figure 7: HRS routing for the vault panels. a) -Y Panel (top left), batteries mounted on external side and not shown. b) +Y Panel (top right). c) -Z Panel (bottom center).

C. RF Panel and Prop Module HRS Control

After the HRS loop passes through the vault, the fluid is routed down to the propulsion module, beginning with the RF panel where the Traveling Wave Tubes and Amplifiers (TWTAs) and radios are mounted. The fluid loop continues on to the RHB, which is thermally isolated from the rest of the propulsion module structure. The RHB is placed downstream of most of the heat-dissipating components in order for the HRS to take full advantage of available waste heat around the flight system; electrical heaters in the RHB supply additional heat to the HRS system when needed.

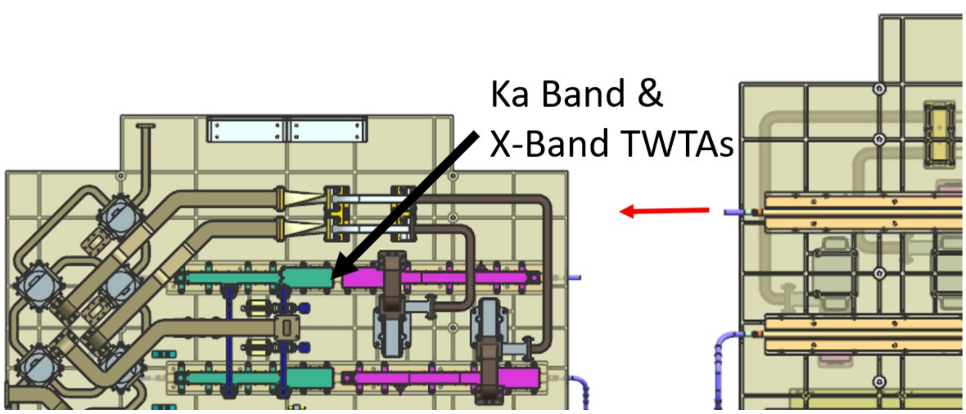

Figure 8: RF Panel. a) Front fiew of the RF panel with the location of the RF hardware (left). b) Back view of the RF panel with the location of the fluid loop routing (right).

The first propulsion subsystem hardware serviced by the fluid loop are the Rocket Engine Modules (REM), which house prop lines and engine valves. There is a temperature delta between the fluid and the engine valves driven by the valves' heat loss through the engine nozzles. Hence, warmer fluid is required to keep the engines at the same temperature than is needed for other prop hardware. This is the primary motivator for having the REMs immediately downstream of the RHB and upstream of the rest of the propulsion module. During inner cruise, the Sun-exposed nozzles are a primary heat load for the HRS that is ultimately rejected out to space through the radiator. The fluid loop and radiator also accommodate transient soak back from engine fires. In between each REM pass, the fluid loop crosses across the Wheel Unit (WU) mounting cone. This set of HRS passes help in fully enclosing the propulsion tanks in a temperature-controlled structure. The propulsion cylinder makes up the rest of the structure enclosing the propulsion tanks and are the last items on the fluid loop before the radiator.

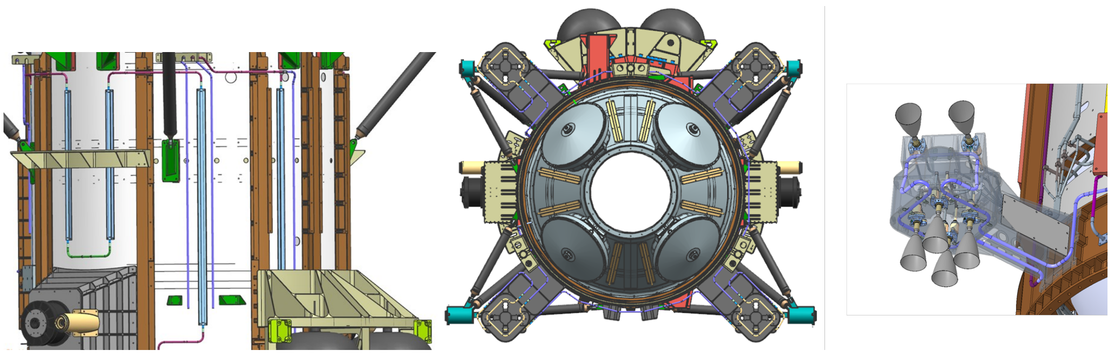

Figure 9: HRS Routing on the Propulsion Module Structures: a) Left Propulsion Module Cylinders. b) Wheel Unit Cone. c) Rocket Engine Modules.

Secondary items temperature controlled by the fluid loop include the propulsion module electronics, the propellant isolation assembly (PIA), and the pressurant control assembly (PCA). Several prop lines internal and external to the propulsion cylinder are temperature controlled via the fluid loop, although some of the external lines do require enhanced conductive and radiative coupling back to the structure.

D. Radiator and Louver Design

The radiator is mounted on the pressurant tank brackets and is the last item on the fluid loop. Its purpose is to reject the total amount of heat required to maintain components coupled to the fluid loop within their maximum AFTs. Because of the strong coupling that the fluid loop provides, the component(s) with the lowest maximum AFT drives the maximum temperatures of the HRS fluid loop; both the batteries and the fuel/ox tank hardware end up being the drivers for Europa Clipper. Although peak heat dissipation occurs during the Europa flybys, the inner cruise scenario is the driving scenario and environment for the radiator size. The HGA acts as a Sunshield for the majority of the spacecraft, but Sun-exposed REM engines and MLI act as large heat loads on to the spacecraft.

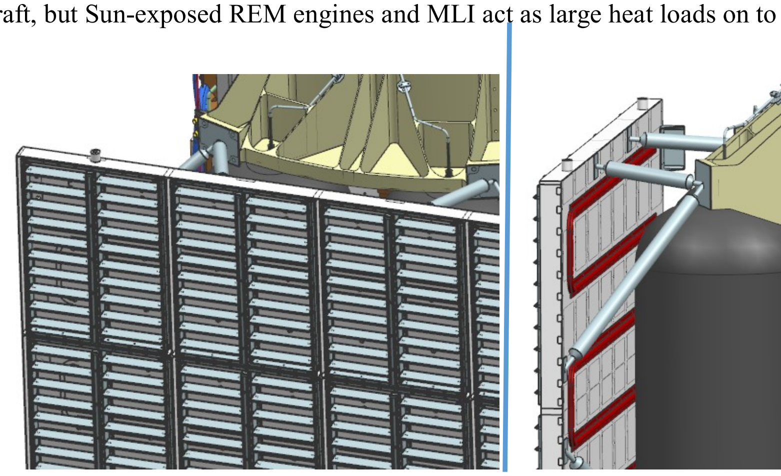

Figure 10: Radiator and Louver design.

The 1.5 m^2 radiator is a 1 mm thick aluminum plate with HRS passes and a guard heater to protect against the CFC-11 freez point of -110℃. The operating temperature range of the radiator is atypical (+30℃ to -95℃ range), and because of the colder operating limit compared to the rest of the spacecraft, the radiator is radiatively and conductively isolated from the spacecraft.

The louvers are used differently from typical flight systems. The purpose of the louvers are to keep the guard heater power demand low; without the louvers about 50W is required to maintain the radiator above the CFC-11 freeze point. However, because of the wide operating temperature range desired (over 100℃), the bimetallic spring is prone to yielding if no modification is done to the louver assembly. This is still an ongoing investigation with power and risk being the primary items to trade.

E. Non-HRS Thermal Control:

Certain spacecraft assemblies have wider temperature requirements allowing for many of these components to be passively thermally controlled. These components include, the nadir deck, magnetometer boom, instrument brackets, instrument sensor heads, RF antennas, and launch locks/release mechanisms. The primary consideration for these passively thermally controlled components is to ensure that they can tolerate expected space environment loads such as inner cruise Sun exposure and long eclipse excursions. These components are also thermally isolated as best as possible to limit heat losses and power demand from the HRS system.

F. Solar Array

The thermal environment heavily influences the solar arrays. At 0.65 AU the solar arrays exceed their allowable temperatures during Sun normal orientations. Hence the spacecraft must maintain the SAs angled off-Sun. Additionally, faults during inner cruise have to be considered. The recovery scheme for these faults are being driven by the maximum allowable temperatures of the solar arrays. At Jupiter, the long eclipses drive the minimum temperatures; temperatures as cold as -238℃ are predicted. These extreme temperatures are driving the solar array mechanical design and options. The drive mechanism, SADA, and its interface to the spacecraft is a critical interface due to the significant heat leak; approximately 45W of heat can be lost through the two SADA mounting interfaces. This has motivated assessment of potential thermal isolation opportunities to reduce the predicted heat loss, although it is a difficult assembly to isolate due to the large deployment mass.

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G. RF Antennas

Similarly, RF antennas are also heavily influenced by the thermal environment. However, there are more options for passive thermal control of this hardware. The HGA acts as a large Sunshield during inner cruise, with tight HGA-to-Sun pointing requirements imposed on the flight system for AU distances less than <2AU. An RF transparent Radome composed of a single layer of stamet coated black kapton, is used to decrease the peak temperatures during closest Sun approach. The MGA, LGAs, and Fanbeam antennas use thermal coatings and MLI blanketing for passive thermal control. All these components are also thermally isolated from the rest of the spacecraft in order to reduce heat loss from the primary spacecraft bus.

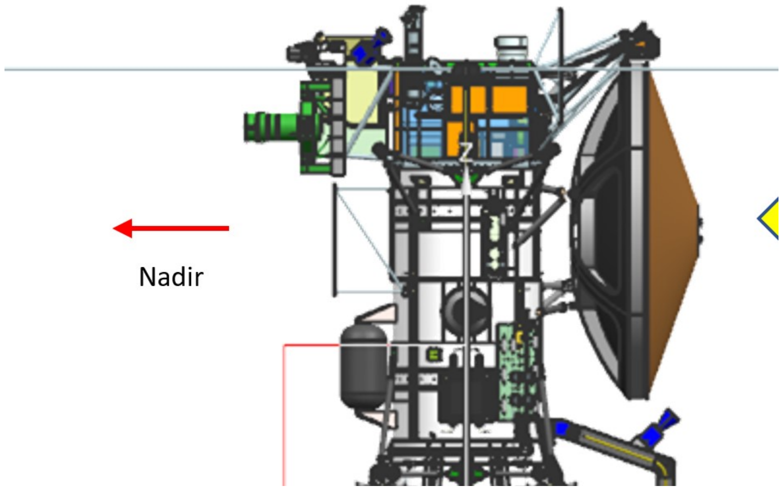

Figure 11: Spacecraft Orientation during Inner Cruise phase of the mission.

H. Nadir Deck and Magnetometer Boom

The nadir deck and magnetometer boom serve as instrument sensor head mounting interfaces. These structures follow the same control philosophy of the RF Antennas: passive thermal control and thermal isolation from the rest of the spacecraft. The nadir deck, being closely mounted to the vault and with relatively high dissipating instrument sensor heads, does not dip to temperatures as low as expected for the boom. The 5-meter long composite boom must tolerate temperatures as cold as -180℃. Since the boom is Sun exposed during inner cruise, exposed metallic fittings need to be considered and assessed carefully. The boom deployment hardware is controlled through flight software controlled heaters. However, these heaters are turned off post boom deployment. Both the nadir deck and Boom have structural pointing and alignment requirements that mandate coupled structure-thermal FEM analysis.

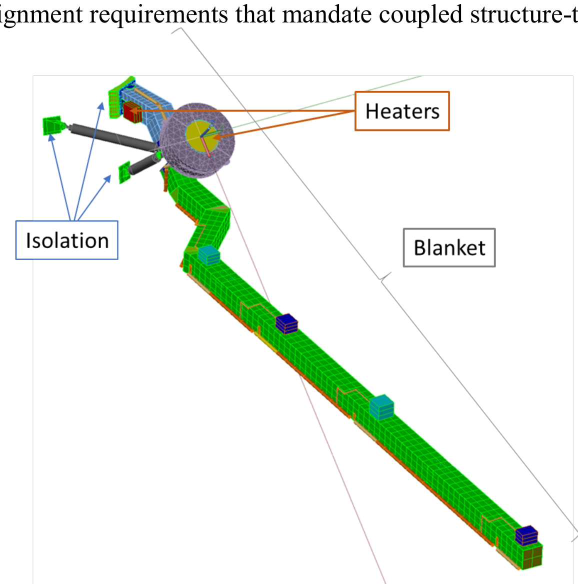

Figure 12: High level description of the boom thermal control.

IV. Conclusion

The Europa Clipper spacecraft must tolerate extreme thermal environments all the while maintaining high energy efficiency due to low power generation capabilities at Europa. The thermal subsystem design is able to accommodate these drivers by employing a mechanically pumped HRS that efficiencly harvests and redistributes heat across the spacecraft. Components that can tolerate wider limits are thermally isolated form the HRS set of assemblies and are thermally controlled via passive means. There is still design development occurring, with additional attention being provided to the louver design, thermal isolation features, and efficient routing of the HRS, all in an effort to continue to maintain an energy efficient thermal control system.

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References

1Ochoa, H., Hua, J., Lee, R., Mastropietro A., Bhandari, P. et al, “Design and Development of the Heat Redistribution System For the Europa Clipper Spacecraft”, 47th International Conference on Environmental Systems, Charleston, SC, July 2017

2Ochoa, H., Bhandari, P., Mastropietro A., Paris, A., “Thermal Control Architecture Trade Study for the Europa Clipper Pre-Project Study”, Thermal Fluids Analysis Workshop, NASA MSFC, August 2015